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Overview of Mollisols in the world: Distribution, land use and management

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Liu, X., Burras, C. L., Kravchenko, Y. S., Duran, A., Huffman, T., Morras, H., Studdert, G., Zhang, X., Cruse, R. M. and Yuan, X. 2012. **Overview of Mollisols in the world: Distribution, land use and management.** Can. J. Soil Sci. **92**: 383–402. Mollisols – a.k.a., Black Soils or Prairie Soils – make up about 916 million ha, which is 7% of the world's ice-free land surface. Their distribution strongly correlates with native prairie ecosystems, but is not limited to them. They are most prevalent in the mid-latitudes of North America, Eurasia, and South America. In North America, they cover 200 million ha of the United States, more than 40 million ha of Canada and 50 million ha of Mexico. Across Eurasia they cover around 450 million ha, extending from the western 148 million ha in southern Russia and 34 million ha in Ukraine to the eastern 35 million ha in northeast China. They are common to South America's Argentina and Uruguay, covering about 89 million and 13 million ha, respectively. Mollisols are often recognized as inherently productive and fertile soils. They are extensively and intensively farmed, and increasingly dedicated to cereals production, which needs significant inputs of fertilizers and tillage. Mollisols are also important soils in pasture, range and forage systems. Thus, it is not surprising that these soils are prone to soil erosion, dehumification (loss of stable aggregates and organic matter) and are suffering from anthropogenic soil acidity. Therefore, soil scientists from all of the world's Mollisols regions are concerned about the sustainability of some of current trends in land use and agricultural practices. These same scientists recommend increasing the acreage under minimum or restricted tillage, returning plant residues and adding organic amendments such as animal manure to maintain or increase soil organic matter content, and more systematic use of chemical amendments such as agricultural limestone to replenish soil calcium reserves.

Key words: Mollisols, chernozems, classification, sustainability, soil quality, tillage systems, fertilization, crops yield

Liu, X., Burras, C. L., Kravchenko, Y. S., Duran, A., Huffman, T., Morras, H., Studdert, G., Zhang, X., Cruse, R. M. et Yuan, X. 2012. **Panorama des mollisols dans le monde : répartition, vocation et gestion.** Can. J. Soil Sci. **92**: 383–402. Les mollisols (sols noirs, sols des prairies) couvrent environ 916 millions d'hectares, soit 7 % des terres émergées sans glace de la planète. Leur répartition est étroitement corrélée avec les écosystèmes des prairies naturelles, mais ne se limite pas à celles-ci. On les retrouve principalement aux latitudes moyennes, en Amérique du Nord, en Eurasie et en Amérique du Sud. Sur le continent nord-américain, les mollisols s'étendent sur au-delà de 200 millions d'hectares aux É.-U., sur plus de 40 millions d'hectares au Canada et sur 50 millions d'hectares au Mexique. En Eurasie, les mêmes sols couvrent près de 450 millions d'hectares, des 148 millions du sud de la Russie et des 34 millions de l'Ukraine, à l'ouest, aux 35 millions du nord-est de la Chine, à l'est. En Amérique du Sud, ces sols se rencontrent couramment en Argentine et en Uruguay, où ils s'étendent respectivement sur près de 89 millions et de 13 millions d'hectares. On considère souvent les mollisols comme des sols productifs et fertiles par définition. On les cultive abondamment et de manière intensive, tout en les consacrant de plus en plus aux céréales, lesquelles exigent d'importants apports d'engrais et des labours. Les mollisols revêtent aussi de l'importance pour la paissance, l'élevage sur grands parcours et la production de fourrages. Par conséquent, il est pas étonnant qu'ils soient enclins à l'érosion, à la déshumification (perte d'agrégats stables et de matière organique) et à l'acidification attribuable aux activités anthropiques. C'est pourquoi les pédologues de toutes les régions de la planète où il y a des mollisols s'interrogent sur la pérennité de certaines tendances actuelles concernant la vocation des terres et les pratiques agricoles. Les mêmes scientifiques préconisent d'augmenter la superficie du sol peu ou pas travaillée, de restituer au sol les résidus végétaux et de le bonifier avec des amendements organiques comme le fumier, afin de préserver ou d'accroître les réserves de matière organique, tout en recourant de façon plus méthodique à des amendements chimiques comme la chaux agricole, afin de renouveler les réserves de calcium.

Mots clés: Mollisols, tchernozioms, classification, pérennité, qualité du sol, systèmes de travail du sol, fertilisation, rendement des cultures

Abbreviations: CEC, cation exchange capacity; SOC, soil organic carbon

Soil classification was established by the Russian scientist V.V. Dokuchaev in the 1870s (Kravchenko et al. 2010a). Dokuchaev devised a genetic classification, which was further refined by Russian, European and American scientists. He identified the five major factors that control soil formation, namely: the nature of the parent material (chemical and mineralogical composition), the climate (especially temperature and precipitation), the influences of organisms – flora, fauna and humans, the topography of the area (relief), and the length of time over which soil formation had occurred (Whalen and Sampedro 2009). Dokuchaev's approach remains important in most, if not all, of the world's major soil classification systems such as the USA's Soil Taxonomy, which recognizes 12 soil orders (Soil Survey Staff 2010).

Central to Dokuchaev's pioneering work, as well as that of Guy D. Smith, the originator of Soil Taxonomy, was understanding and classifying soils formed under prairie ecosystems. These soils were and still are crucial to their respective countries' agriculture. Most soils that formed under prairie are classified as Mollisols in the United States system of soil taxonomy. Mollisols are identified by a thick, dark-colored, humus and base-rich surface horizon (mollic epipedon) with a high base saturation ($\geq 50\%$ by ammonium acetate) to 1.8 m depth (Soil Survey Staff 2010). They generally have a high cation exchange capacity (CEC) throughout their sola. The CEC of the upper profile is derived from humus with pH-dependent charge and clay-sized phyllosilicates having permanent charge. In the lower profile, the CEC is nearly exclusively from clay-sized phyllosilicates such as smectite, vermiculite, or illite. Calcium is generally the main exchangeable cation throughout the profile. Most Mollisols contain a significant content of weatherable minerals in their silt and sand fractions. In summary, there are nine criteria defining the mollic epipedon (Soil Survey Staff 2010), and they have a surface mineral horizon at least 25 cm thick with (a) structure, (b) moist color with both chroma and value being 3 or less, and (c) at least 50% base saturation and 0.6% organic carbon content (Burras et al. 2010). However, classification and modifications of mollic epipedon thickness criteria for eroded Mollisols were recently proposed by Olson et al. (2005a, b).

Mollisols are known in other soil classification systems as Chernozems (Russia, FAO), Kastanozems and Phaeozems (FAO) and Isohumosols or Black Soils (China). In the National Soil Classification System of Uruguay, they are included in the Great Groups of Brunosols and Argisols (Duran 2010). The Soil Taxonomy is officially used in Argentina. The Canadian system of soil taxonomy does not specifically identify Mollisols, but the Chernozemic, Solonchic and Vertisolic Great Groups are those which most closely fit the diagnostic criteria. For the purposes of this overview,

the terms "Black Soils", "Chernozems" and "Mollisols" are used as synonyms.

The natural areas of occurrence of these soils are the prairies and steppes of the temperate earth. More specifically, Mollisols are most extensive in mid-latitude, mid-continental locations, but are also recognized in some colder and drier climates. There are even minor areas of Mollisols in the tropics and subtropics. On a world-wide basis, soil scientists generally speak of four main major regions of Mollisols. One is located in central North America radiating across the central plains of the United States and southern Canada. The next two appear as a discontinuous belt, which extends across southeastern Europe and central Asia. The western belt begins in the sub-humid steppes of south-central Europe and extends across Russia and into the eastern belt, which is best represented in northeast China. The fourth major region corresponds to the Pampas of South America, covering most of central-eastern Argentina and almost all of Uruguay. Thus, most of the world's 916 million ha of Mollisols occur in three regions of the northern hemisphere and one region south of the equator, the Parana-La Plata basin of South America. The understanding of this distribution as well as the formation, uses and risks of these soils, is crucial given that these four Mollisol regions collectively form the world's natural granary (Liu et al. 2010). Intensive cultivation, soil organic carbon (SOC) loss, soil erosion and associated yield suppression are still the problems that threaten the future sustainability of agriculture in different Mollisol regions.

This review paper introduces the Mollisols of the world with emphasis on United States, Canada, Russia, Ukraine, northeast China, Argentina and Uruguay in terms of their geographical distribution, land use, and management. The discussion herein rests primarily on literature from throughout the world's Mollisol regions. When specific and/or unpublished data are used, they are credited to the originating scientist and study.

DISTRIBUTION

Distribution in North America

Mollisols are the most common soils in North America, covering more than 200 million ha in the United States or 21% of the country (Soil Survey Staff 2010), more than 40 million ha in Canada (Soil Landscapes of Canada Working Group 2011) and about 50 million ha in Mexico. They are most extensive in the central plains, extending from the prairie provinces of Canada across the USA's Great Plains and into eastern Mexico's semi-arid grasslands (Fig. 1). Sizeable areas of Mollisols are present in the more mountainous, semi-arid western USA and there are even locally important regions of Mollisols in the humid southeast USA, especially in Florida. In sum, North American Mollisols occur where mean annual precipitation is as high as 1500 mm to as low as 500 mm and where mean annual temperature is

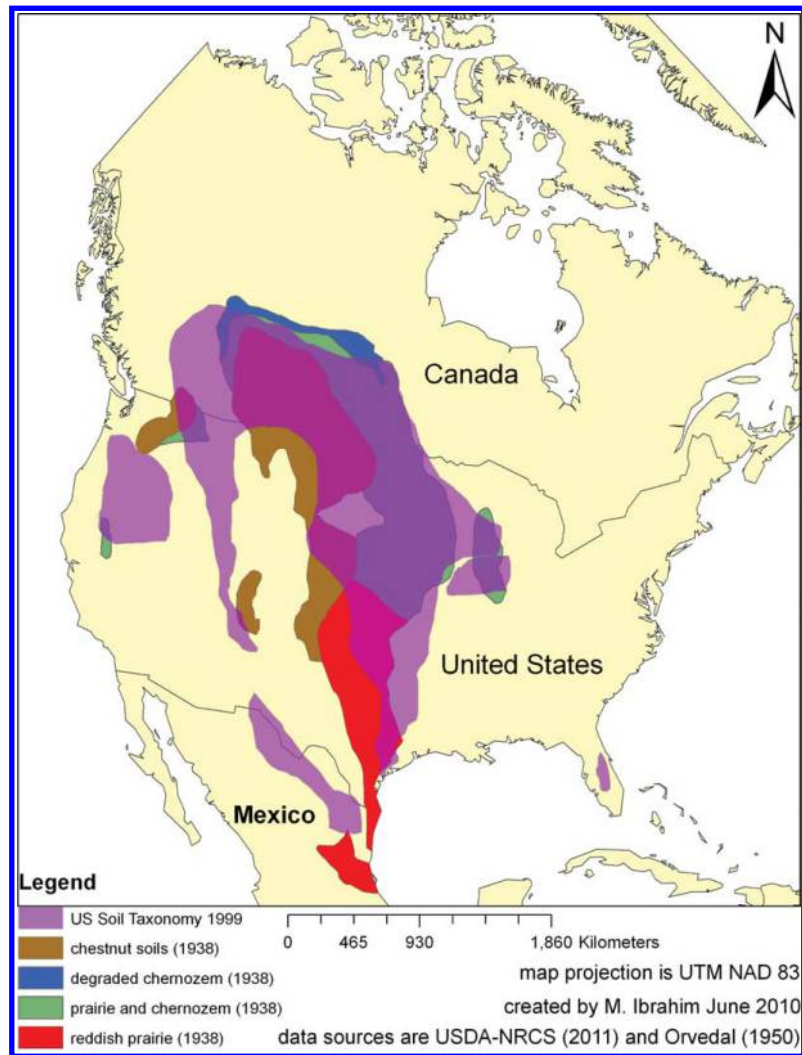


Fig. 1. Distribution of Mollisols across North America.

as high as 20°C to as low as 5°C. Most of the Mollisols of North America, though, are found at the middle of these ranges in rainfall and temperature.

The distribution across much of North America suggests their formation requires only two features: (a) fertile parent material, and (b) biota that results in humus formation to a depth of 25 cm or more. This former feature is most commonly associated with Pleistocene-aged sediments, especially till, loess and alluvium. The latter feature is normally the result of prairie ecosystems, which are known for their perennial, deep, fibrous root systems with slow decomposition to form metastable Ca-humic materials (Fenton 1983; Anderson 1987). Mollisols in the United States are formed mostly in Quaternary materials on gentle or moderate slopes. They occur in a wide range of landscapes ranging from flat alluvial plains to undulating plains and mountains (Fenton 1983). In addition to their mollic epipedon, Mollisols in the USA routinely have

any of a number of other diagnostic horizons such as argillic horizons, calcic horizons, cambic horizons and natric horizons. There are even about 1 million ha of Mollisols with albic horizons within the USA (Soil Survey Staff 1999). The Canadian system of soil taxonomy does not specifically identify Mollisols, but the Chernozemic, Solonchic and Vertisolic Great Groups are those which most closely fit the diagnostic criteria. These soils developed under semi-arid to sub-humid grassland and parkland ecosystems in southern Manitoba, Saskatchewan and Alberta and in the interior valleys of British Columbia.

Distribution in Russia

Soil classification in the Russian Federation and Ukraine is still based on genetic principles proposed by V. V. Dokuchaev (1883). Chernozems are divided into five subtypes: “Podzolized”, “Leached”, “Typical”, “Ordinary” and “Southern”. Russian Chernozems are

distributed within 50° to 54° of northern latitude and extend from the border with Ukraine in the west to the Yenisei River in the east (Fig. 2). Chernozems podzolized, leached and typical cover 45 million ha while meadow-chernozems cover 13.5 million ha. In the Steppe region, 52 million ha are Chernozems ordinary and southern, and 11.5 million ha are meadow-chernozems. Besides, 11 million ha of Kashtanozems (Chestnut Soils) as well as 15 million ha of Dark Forest Soils could also be added to Chernozems order. Total area of Chernozems accounts for 52.6% of arable lands in the Russian Federation and approximately 72% of these soils have been cultivated (Dobrovolskiy and Urusevskaya 2004).

The climate of the Russian chernozemic zone is warmer in the west and more continental in the east, becoming more mild and rainy in the Pacific Ocean direction. Russian Chernozems occur where the mean annual temperature is from (–) 4°C to (+) 8°C. Within this region, the annual sum of the temperature exceeding 10°C is from 1400°C to 3200°C, and the amount of solar radiation is from 40 to 60 kcal cm² yr^{–1}. The average annual precipitation is from 350 to 700 mm. The growing period ranges from 90 to 160 d. The topography of the zone is characterized by severely eroded uplands, which are common to the eastern European Plain. The majority of Chernozems are formed on sandy and clastic (gravelly to cobbly) alluvial-colluvial deposits. They are mostly light and medium loams in the northwest and heavy loams and clays in the southeast. They generally lack gypsum and soluble salts. The natural vegetation is forests with grasses, with xerophytic and halophytic species dominant in the south.

The Chernozem region is characterized by severe winters, with soils routinely freezing to depths of 2 m, and late thawing. These cold winters foster humus accumulation in the range of 5 to 11% in the upper profile (Sokolov and Fridland 1974). The total organic matter and nitrogen storage in Chernozems is 80–220 and 4–15 Mg ha^{–1}, respectively, while the total phosphorus and potassium is 0.1–0.3 and 2.5–3%, respectively, in 0–20 cm layer. Chernozems are endowed with active Ca-phosphates (51–67%). The amounts of Al- and Fe-phosphates decrease with the soil depth. The CEC in Chernozems decreases from 35–60 meq 100 g^{–1} in the eastern European area to 25–35 meq 100 g^{–1} in Siberia. Hydrogen saturation increases from southern to podzolized Chernozems; thus, the acidity in Chernozems is from alkaline to subacid.

Distribution in Ukraine

Ukrainian Chernozems developed on loess and loess-like sediments cover 25.6 million ha, while those developed on eluvium of limestone, sandstone and slates are 1.8 million ha. Dark forest soils with chestnut properties are 6.6 million ha (Tyhonenko et al. 2009). There are 34 million ha of cultivated Chernozems, which account for 62% of all agricultural lands in Ukraine and approximately 78% of these soils have been cultivated (Kravchenko et al. 2010b). These soils are located in a 737 km north–south zone occurring from lat. 51°18'N to 44°41'N and a 1144-km-long east–west zone located from long. 24°18'E to 40°12'E. Ukrainian Chernozems are distributed in the Forest-Steppe and Steppe zones of Ukraine, with deciduous forests being the native vegetation in the west (pre-Carpathians) to the Forest zone in the north, and ending along the Black and Azov sea

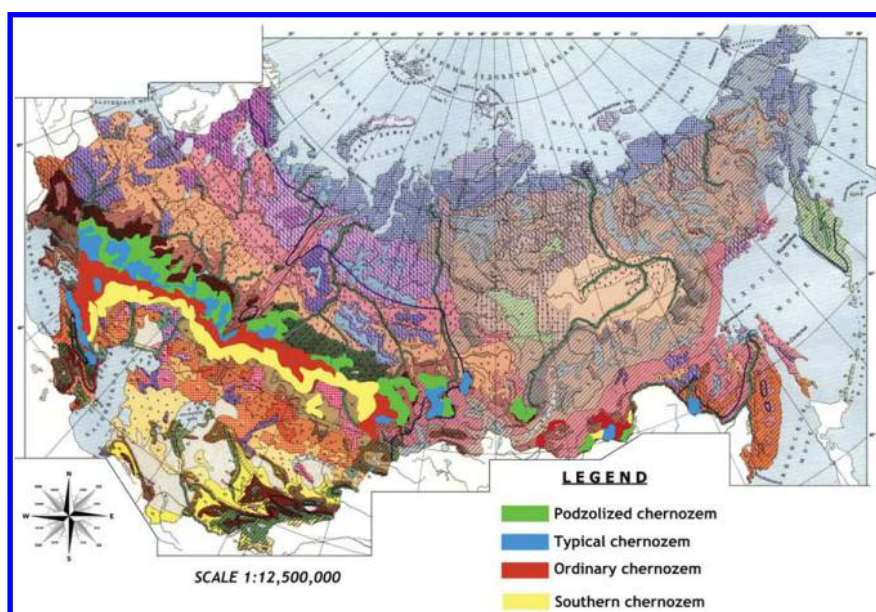


Fig. 2. Distribution of Russian Chernozems.

coasts (Fig. 3). The climate in the Forest-Steppe zone with podzolized, leached, and typical Chernozems is slightly warmer and milder than in the Forest zone. The amount of solar radiation is 98 to 112 kcal cm² yr⁻¹. Mean annual temperature is 7.0 to 7.7°C. The maximum frozen depth is 38 to 74 cm. Frost-free duration is 245 to 270 d. The annual sums of temperatures exceeding 10°C range from 2500°C to 3000°C. The average annual precipitation is generally 490 to 550 mm although in some regions it reaches 650 mm.

The Ukrainian Chernozems are located on a plain, physiographically speaking. It is a geologically nonuniform region. The podzolized and leached Chernozems are distributed across the well-drained uplands of the Forest-Steppe and watersheds. The typical Chernozems are widespread on upland plateaus between river valleys and terraces. Ordinary Chernozems occur everywhere in the northern subzone of the Steppe, covering the watershed plateaus. Southern Chernozems are common across the Black Sea lowlands and mid-Crimean peninsula, as well as being found on the flat plateaus of the South Steppe.

In spite of their common Black Soil features, Ukrainian Chernozems vary in many properties. Soil texture changes from light loams to medium clays, becoming finer from the north to the south and southeast. The clay fraction mineralogy is 60 to 85% hydromicas, 3 to 29% kaolinite, 10 to 46% mixed layer silicates (hydromicas and montmorillonite), and 2 to 20% chlorite. Soil organic matter content in the surface layer ranges from less than 3 to over 5.5% and reaches up to 12% in virgin Chernozems. The humus type (a ratio of the carbon content in humic to fulvic acids, i.e., Cha/Cfa) changes

from fulvate-humate (1.13) to humate (2.9). The soil bulk density is favorable for plant growth, being in the range of 0.9 to 1.3 g cm⁻³. Particle density is 2.60–2.68 g cm⁻³ (Fridland et al. 1981). Chernozems have about 50–60% porosity by volume. Soil pH is 6.7, 7.5 and 8.2–8.6 in podzolized, southern and loess parent materials Chernozems, respectively. These soils are enriched with exchangeable cations (25–50 meq 100 g⁻¹), with the CEC routinely being 80 to 90% Ca-saturated. Chernozems have the highest nitrogen storages among Ukrainian soils. The total nitrogen content ranges from 0.17 to 0.30%, where mineral forms, nonhumic organic compounds, humic acids, fulvic acids, and insoluble residue account for 2, 35, 26, 12, and 25%, respectively. The readily hydrolyzed nitrogen is 127 to 347 mg kg⁻¹. The total phosphorus storages in the 0–100 cm layer range from 17.4 to 22.9 Mg ha⁻¹, while total potassium is 190 to 300 mg kg⁻¹. The available phosphorus and potassium for plants are 7 to 15 mg 100 g⁻¹ and 10 to 37 mg 100 g⁻¹ respectively (Nosko et al. 1988).

General Distribution in South America

The South American Mollisols extend principally over the Chaco-Pampa region together with patches in Patagonia and Mesopotamia regions in Argentina (887 thousand km², 32% of the territory) (Fig. 4) and most of the Uruguayan territory (130 thousand km², 75% of total land) (Fig. 5). Minor areas of occurrence are also found in southern Brazil (42.6 thousand km², about 0.5% of the country) (Palmieri et al. 2002) and in isolated locations in other countries. The majority of South American Mollisols are located in the temperate zone; the mean annual temperature ranges from 14°C in



Fig. 3. Distribution of Subtypes in Ukrainian Chernozems.

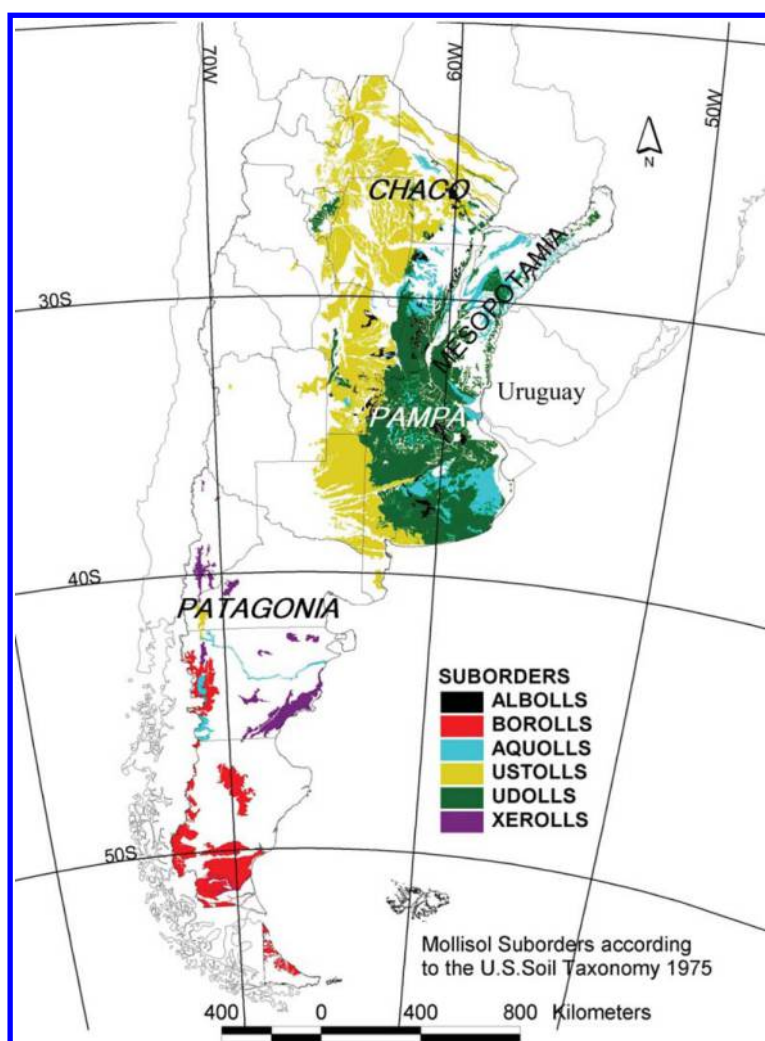


Fig. 4. Geographical distribution of Mollisol suborders in Argentina (SAGyP-INTA, 1990) based on 1975 edition of the US Soil Taxonomy.

the southern limit of the Argentine Pampa to 19°C in northern Uruguay. Winter are mild everywhere and generally are without snowfall except during infrequent extreme events. Frosts, although not very severe, can be expected in the Pampean region over a period ranging from 125 d in the west to only 20 d in the east (Burgos 1963). In Uruguay, the frost free period is 250 d in the central region, 340 d in the north and 320 d in the south. Mean annual precipitation ranges from 500 mm in the southwest of the Pampa (Argentina) to 1500 mm in northeastern Uruguay. The soil hydric balance is positive in the eastern Argentina with 100 mm excess, while marked deficits appear in the west. In Uruguay, the soil hydric balance follows the trend in eastern Argentina, and the annual water excess is 150 to 200 mm in the west, and 300 to 350 mm in the east and northeast.

All the Pampean (Argentine) Mollisols have a thermic temperature regime although some border on mesic. The moisture regimes are mostly udic and ustic. In Uruguay,

the temperature regime is thermic, or even hyperthermic in the extreme north. The soil moisture regime is generally udic. Aquic Mollisols are widespread and are particularly extensive in the Depressed Pampa and in the southern Chaco lowlands of Argentina.

The Pampa region is a vast and continuous plain, rising slightly and gradually to the north and to the west where total flat areas alternate with slightly undulating plains and rolling landscapes. The most recent Quaternary rocks lying on the surface and therefore the parent material of Pampean Mollisols are loess and loessoid sediments to the east and aeolian sands to the west of the region (Iriondo and Kröhling 1996; Morrás and Cruzate 2000; Zárate 2005).

Differing from the typical loess in the northern hemisphere where quartz ranges between 50 and 70% (Pye 1987), the light mineral suite in the Pampean loess is generally dominated by the abundance of volcanic glass, with more pyroxenes and amphiboles in the heavy

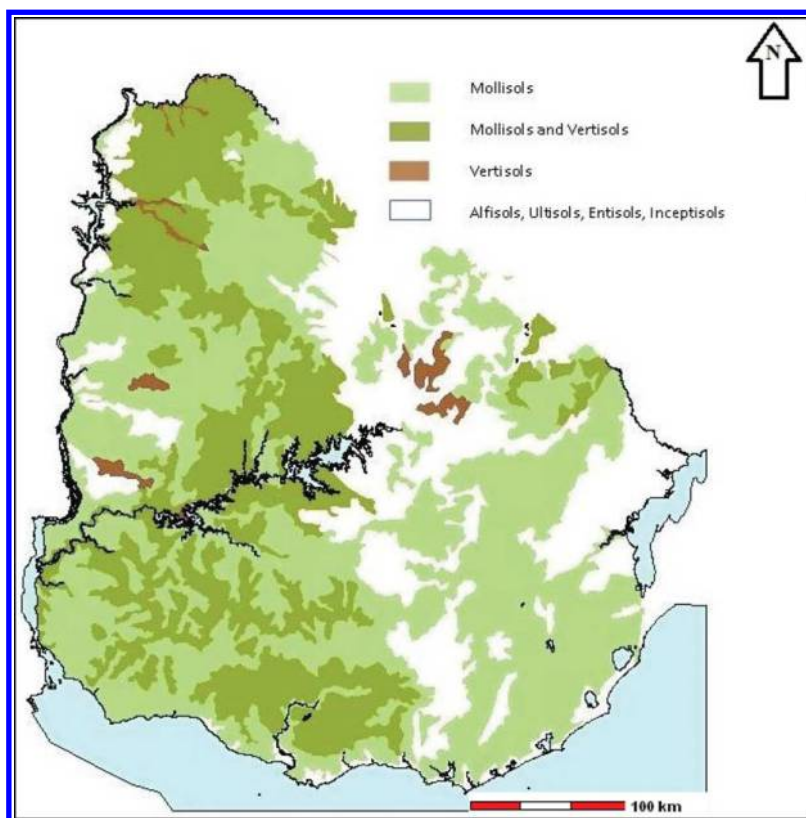


Fig. 5. Geographical distribution and relative importance of Mollisols and Vertisols in Uruguay (Califra and Duran, unpublished).

fraction (Teruggi 1957; Zárate and Blasi 1991). With regard to the clay fraction there is a clear dominance of illite in the west and an increase of smectite and interstratified illite-smectite to the east, close to the Parana River (Iñiguez and Scoppa 1970; Stephan et al. 1977; Morrás et al. 1982; Nabel et al. 1999).

Mollisols of Uruguay and Brazil are distributed on the southern border of the Brazilian shields of Precambrian age outcropping on the eastern side of the continent. Regarding mineralogy, the clay fraction of Uruguayan Mollisols is currently dominated by the combination of illite and smectite with minor amounts of kaolinite. Vertic Mollisols have larger amount of smectite, while other subgroups are higher in illite. Most Mollisols developed on metamorphic rocks have similar amounts of illite and kaolinite, but lack smectite.

Distribution in Argentina

Mollisols are the most representative soils in the Pampa grasslands although they are also widely distributed in association with several other dominant soil Orders in the northern Chaco and Mesopotamia subtropical regions, as well as in the cold-temperate Patagonia in the extreme south of Argentina (SAGyP-INTA 1990) (Fig. 4). All Suborders of Mollisols are found in the country, the most extensive being Udolls and Ustolls. The Great Group of Argiudolls is undoubtedly the most

characteristic of the Argentinean Pampa as well as the most productive and where agricultural activity is more intense. A synopsis of the Suborders distribution according to the more recent version of the Soil Taxonomy (Soil Survey Staff 2010) is the following:

Aquolls: The Mollisols affected by wetness and local topography occur mainly in the eastern part of the country, from 65°W to 55°W. They are well represented in the subsident large areas of the Depressed Pampa and the Subsouthern Lowlands (Bajos Submeridionales) in the southern Chaco, where *Natraquolls* occupy extensive areas and have drainage and management limitations. These areas are devoted to extensive livestock raising on natural grasslands. The Aquolls are also present in the Delta and islands of the Parana River. These soils also have some representation in the humid pre-Andean northwestern Patagonia.

Albolls: With a lower representation than the Aquolls, Albolls occur in flatlands and concave areas with a seasonal water excess enhanced by argillic or natric horizons, particularly in the northern Pampa and southern Chaco, and in the Mesopotamian Corrientes Province. They also appear in lower proportions in western Provinces.

Udolls: Udolls are the main soils in the grasslands of the humid Pampa, particularly in the Buenos Aires and Santa Fe Provinces. They also appear in lower proportion in the Chaco and Mesopotamia regions and in humid areas of northwestern Argentina. These soils usually display an argillic or a cambic horizon. The *Argiudolls* developed on loessic sediments and under a tall-grass prairie are the typical and more productive soils in the eastern Pampa region. These soils also appear in some areas in the Mesopotamia region and in patches in the northwestern Tucumán and Santiago del Estero Provinces. The *Hapludolls* are represented to a lesser extent in the humid Pampa, which have a cambic horizon and are quiet suitable for crop productions. The *Paleudolls* are localized in some areas of Buenos Aires and Corrientes Provinces.

Ustolls: These Mollisols extend along a subhumid-semiarid belt in the center of the country, more or less coincident with the meridian 55°W, from the temperate southern part of the Pampa to the warm northern Chaco, up to the border with Paraguay and Bolivia. A patch of Ustolls also occurs in the pre-Andean area in the Rio Negro Province. Ustolls cover a considerable area in the Santa Cruz and Tierra del Fuego Patagonian provinces. These Mollisols have a diversity of subsurface horizons as cambic, argillic, natric and albic. *Haplustolls* are well represented along the subhumid Pampean region, where they are used for livestock and agricultural production; these soils are also extended in the northwestern part of the country, and localized in several other regions as well. In Patagonia they account for 5% of the total area. *Calcistolls* also appear in the western Pampa, while *Argistolls* are more extensive in northwestern Argentina. *Natrustolls* cover limited areas in the Pampa and Chaco regions. *Paleustolls* appear to a limited extent in ancient and stable surfaces in northwestern provinces (Catamarca, Salta, Jujuy, and Tucuman) and *Durustolls* are scarcely represented in the Chaco region.

Xerolls: These soils occur in limited extent in several areas in Patagonia, and usually have a thin mollic epipedon followed by an argillic or cambic horizon.

Rendolls: These soils are restricted to fossil shell banks deposited during recent Quaternary marine incursions in the northeast of the Buenos Aires Province, and characterized by their xerophytic forest.

Cryolls: These are soils of cold regions, developed in some areas in the Andean ranges of western humid Patagonia down to Tierra del Fuego. Mollisols with a cryic soil temperature regime were included within the Borolls suborder in the 1975 edition of the US Soil Taxonomy.

Gelolls: Some pedons that can be classified in this new suborder of the Soil Taxonomy have been described in

the Antarctic area claimed by Argentina (Godagnone and de la Fuente 2010).

Distribution in Uruguay

Uruguay has zones of pure Mollisols, pure Vertisols and Mollisol-Vertisol mixtures (Fig. 5). The Vertisols are mentioned because, at least in Uruguay, they have many properties similar to Mollisols, such as high organic matter content. Thus, the occurrence of Vertisols is strongly associated with Mollisols. Mollisols are distributed all over Uruguay, especially in the western half of the territory. Mollisols in the western region are more fertile, richer in organic matter, more resistant to water erosion than those in the eastern part of the country. Mollisols of Uruguay are very dark brown, very dark gray or black both in the A and B horizons. The thickness of the two horizons is 90–120 cm except a hard rock substratum, which is shallower. Mean clay content is 25% in the A horizon and 46% in the B horizon. The clay content in the topsoil varies widely and is as high as 40% in weakly developed soils from fine textured sediments or as low as 10% in soils from sandstones. Soil organic carbon is 2.7% in the topsoil and 1.1% in the B horizon. From a total of 250 mollic epipedons investigated, 60% are thicker than 50 cm and 75% are 30 to 80 cm thick. The mean SOC content of the epipedon is 12.3 kg m⁻² though the range is wide, which is more related to the variation in epipedon thickness than to the carbon content. Mollic epipedons less than 20 cm thick are rare and always occur in shallow pedons belonging to lithic subgroups. Vertisols have a mollic epipedon, finer texture with 43% clay in the topsoil and 3.9% organic carbon content in the A horizon. Smectite is clearly dominant in the clay fraction.

Mollisols in Uruguay are developed from wide variety of sediments – mostly fine or medium texture and from basalt. On the acid crystalline rocks of the Precambrian shield, Mollisols have a reddish brown or red argillic horizon, a sandy loam A horizon overlying a clay loam or clay B horizon. A stone line between the two horizons is often shown. They have neither swelling clays nor free carbonates and are more acid in depth. Base saturation does not increase significantly in the lower horizons (B and C) as it does in other Mollisols. Albolls, Aquolls and Udolls Suborders of Mollisols occur in Uruguay (Duran et al. 2005).

Distribution in Northeast China

The Mollisols of Asia are primarily located in China, especially in northeast China. Northeast China includes Heilongjiang Province, Jilin Province, Liaoning Province and the Hulunbeier League of the Inner Mongolian Autonomous Region. The region is located between lat. 38°43'–53°33'N and long. 115°31'–135°05'E. The total area is 124.9 × 10⁴ km². The region is 1600 km long in the east–west axis, and 1400 km wide in the north–south axis (Zhang and Sui 2010). Mollisols developed in this region

are mostly from Steppe, Prairie to Forest-Steppe vegetations (Fig. 6). Geomorphologic landscapes in the region are plain terraces and tablelands. Most of region has undulating to rolling topography with gentle slopes in the range of 1 to 5°. The elevation is around 150 to 400 m. Mollisols are developed from quaternary loess-like sediment. The thickness of loess-like materials is 10 to 15 m. The soils and their parent materials are generally slightly acid to alkaline. The soil texture ranges from loam to light clay, with most sola being predominantly clay loam. The main clay mineral is illite although some chlorite and montmorillonite is found in some profiles. The accumulation of soil organic matter is the main process of Mollisols formation. Many other processes are also involved. They are clayization, (a.k.a, neoformation), eluviation and illuviation, leaching and reprecipitation of carbonate minerals, oxidation and reduction of iron and manganese, salinization, desalinization and albic bleaching. These processes divide the Mollisols into different Suborders and Great groups (Gong 2007; Zhang and Sui 2010).

Mean annual temperature in the region is -2.5 to 5.6°C . The annual accumulated temperature ($\geq 10^{\circ}\text{C}$) is 1600 – 3000°C . The frost-free period is 100 to 140 d, and the depth of frozen soil is 1.1 to 2.0 m. The mean annual

precipitation is 300 to 600 mm, which occurs in the summer. Although the total area of Chinese Mollisols covers $124 \times 10^4 \text{ km}^2$, accounting for 13.5% of the world total (IUSS Working Group WRB 2007), the continuous pure area of Mollisols in northeast China is $34.8 \times 10^4 \text{ km}^2$. Over one-half of these occur in Heilongjiang Province (i.e., 54.5% of the China's total area of Mollisols). Hulunbeier District of Inner Mongolian autonomous region and Jilin Province have 22.5 and 19%, respectively, of China's Mollisols while Liaoning Province only accounts for 4.0% of the total (Zhang and Sui 2010). The mollic horizon or epipedon of these soils normally ranges from 30 to 70 cm, but can be up to 100 cm thick, depending on locations (Xing et al. 2004). Although some areas of Black Soils areas were cultivated 200 yr ago, most of these soils have been under agricultural production for about 50 yr. SOC content in the surface layer (0–17 cm) of the typical Black Soil in the area is 28.1 – 54.4 g kg^{-1} , CEC is 31.5 – $45.8 \text{ meq } 100 \text{ g}^{-1}$, while soil bulk density is around 1.39 – 1.09 g cm^{-3} (Liu et al. 2003). The average thickness of the topsoil layer in 1982 was 43.7 cm, and area with thickness of the topsoil layer less than 30 cm accounted for 40.9% of the total in 2002 (Zhang et al. 2007).

LAND USE

Land Use in the United States of America

Most Mollisols in the United States of America were converted to agriculture from native prairie or open park ecosystems in the 19th century. The predominant land use is intensive cereal or livestock agriculture (Soil Survey Staff 1975, 2010). The four most common grain crops on Mollisols are maize, soybean, wheat and sorghum (Padgett et al. 2000). In regions where precipitation exceeds 1000 mm they are routinely used to grow maize (*Zea mays*) and soybeans (*Glycine max*). In sub-humid and semi-arid areas, they are more commonly farmed for wheat (*Triticum aestivum*) and other small grains, or irrigated and used to grow maize, rice (*Oryza sativa*) and a myriad of other crops. Poorly drained Mollisols are routinely artificially drained via tile (perforated subsurface pipes) and drainage ditches in order to facilitate extensive crop growth. The crop rotation of most Mollisols is very simple, e.g., 1 yr of maize followed by 1 yr of soybeans, followed by 1 yr of maize, etc. Across all climates in North America, Mollisols support livestock agriculture through pastures and forage crops such as alfalfa (*Medicago sativa*). Mollisols are extremely productive even in dryland agriculture. For example, dryland maize grain yields of 12 Mg ha^{-1} are common in Iowa, and yields of dryland soybeans are more than 4 Mg ha^{-1} (Miller 2010). Forage crops have comparable high yields. These yields are comparable to those of other major Mollisol states such as Illinois, Minnesota, Missouri, and Nebraska. Land area devoted to different crops in

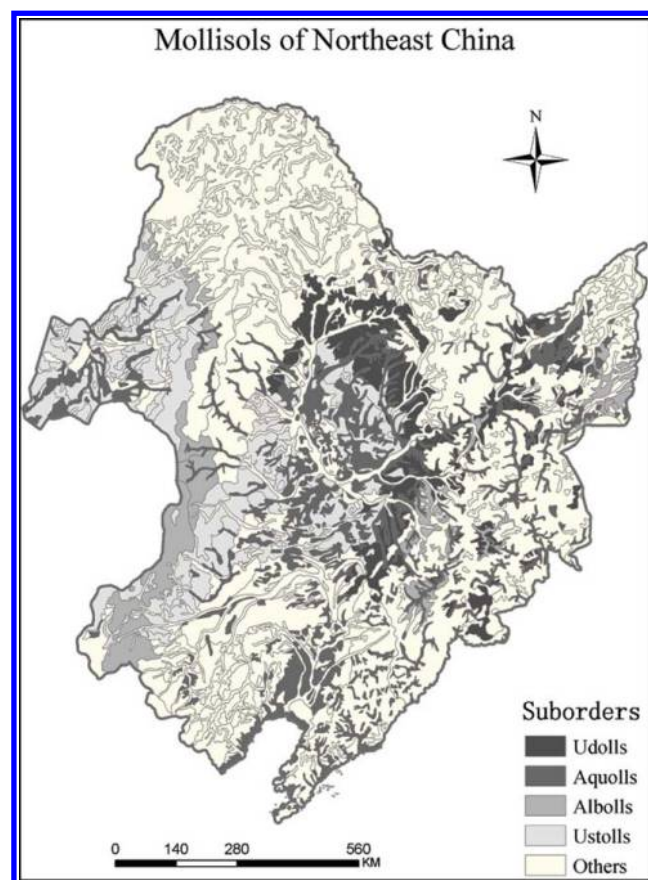


Fig. 6. Distribution of Mollisols in northeast China.

the Mollisol area has changed since 1868 as illustrated in Fig. 7, using Iowa as an example. Row crops are replacing small grains and perennial crops.

Land Use in Canada

Cultivation of Chernozemic soils (Mollisols) in Canada began in the Red River Valley of Manitoba early in the 19th century and expanded into the more arid regions to the west over the following 120 yr. By the latter part of the 20th century, most of the land with capability for crop production was under cultivation, while many areas less suitable for crops had been broken and subsequently returned to rangeland as a result of the “dust bowl” drought of the 1930s. Most of the land areas that are not suitable for annual cropping support livestock grazing. Changes in the distribution of the primary land use types are presented in Fig. 8. The primary crops produced are wheat, barley (*Hordeum vulgare*), oats (*Avena sativa*), canola (*Brassica napus*), flax (*Linum usitatissimum*) and perennial forages for hay and pasture (Statistics Canada 2007). In the more humid regions of southern Manitoba, maize, soybean and sunflower (*Helianthus annuus*) are also grown, while localized areas of irrigated alfalfa (*Medicago sativa*), potato (*Solanum tuberosum*), grain and sugarbeet (*Beta vulgaris*) occur near sources of surface water throughout the region. Creeping red fescue (*Festuca rubra*) is also produced as a commercial crop in the most northerly areas. Summer fallow (leaving the land uncropped for one growing season in order to conserve moisture and control weeds) has traditionally been a standard practice in the arid and semi-arid portions of the prairies, but since the 1980s the area of summer fallow has declined steadily, while the cultivation of pulse crops such as lentils (*Lens culinaris*) and dry field pea (*Pisum sativum*) has increased dramatically. In the semi-arid southwest portion of the prairies wheat in rotation with summer fallow every 2 or 3 yr and cattle ranching are common, while in the more humid regions to the north and east

continuous rotations of cereal grains and oilseeds are common and summer fallow is used less frequently.

Land Use in Russia

Among the 221 million ha of agricultural land, 55.1% is cropland, 30.9% is pastureland, 10.9% is hayland, and 2.3% is abandoned lands. Agricultural enterprisers account for 67.4% of the total land, while private owners cultivate only 32.6% of these agricultural lands (Laykam et al. 2009). Agricultural crops are grown according to climate conditions and type of soils. The acreage planted in wheat, maize, barley and leguminous crops covers more than 92% of the total. Market behavior also affects the farm specialization (Sokolyn et al. 2009). The central zone of Russia with podzolized, leached and typical Chernozems in warm-temperate climate is used to grow flax, rye (*Secale cereale*), barley, potato, pea (*Pisum sativum* L.), lentil, lupine (*Lupinus* spp.), garlic (*Allium sativum* L.), and fodder production. Winter wheat, sugar beet, cherry (*Prunus cerasus*), hazel (*Corylus avellana* L.), plums (*Prunus domestica* L.), apples (*Malus domestica*), and pears (*Pyrus* L.) are widespread in any Russian chernozem regions. In the south, heat-tolerant plants, such as oat, buckwheat (*Fagopyrum esculentum*), rape (*Brassica napus* L.), haricot (*Phaseolus vulgaris*), millet (*Setaria italica*), onion (*Allium cepa* L.), vegetables are included in the crop rotation. Winter wheat, corn, sunflower, watermelon (*Citrullus lanatus* Thunb.), pumpkin (*Cucurbita*), tomato (*Solanum lycopersicum* L.), and eggplant (*Solanum melongena* L.) are grown in ordinary and southern Chernozems. In the semi-humid and semi-arid regions, quince, *Circassia* walnut, sweet cherry, peaches (*Prunus persica*), apricots (*Prunus aemeniaca*) are planted. Starting from Pre-Ural region, only spring cereals are cultivated on podzolized, leached and typical Chernozems. In the far-east region, soybean, potato, vegetables, and cereals are planted. The revenue of plant production in this area accounts for 52.9% of

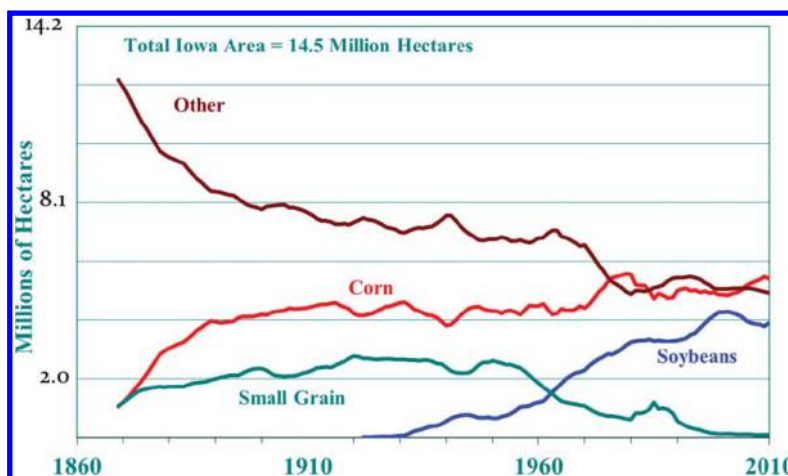


Fig. 7. Changes in land area devoted to different crops in Iowa from 1868 through 2010.

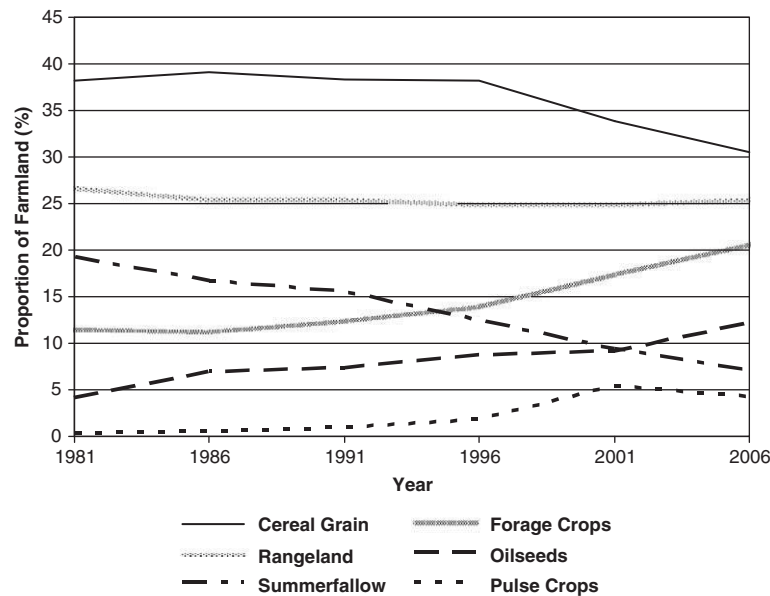


Fig. 8. Distribution of main land use types on Canadian Mollisols, 1981–2006.

the total agricultural sector, while animal production accounts for 47.1% (Statistics of Russian Regions 2009).

Land Use in Ukraine

Among all the cultivated Chernozems, 49.8% are used by so-called economic partnerships, 28.4% by private enterprises, 8.5% by production cooperatives, 2.4% by state enterprises, and 10.9% by others. The structure of agricultural lands is: 32.4 million ha of croplands, 2.41 million ha of haylands, 5.5 million ha of pastures, 0.9 million ha of perennial crops, 0.4 million ha of abandoned lands, 1.41 million ha of fallow. Crop acreage in Ukraine depends a lot on soil climatic factors and local specializations in agricultural enterprises (Table 1).

Production of grain and leguminous crops has doubled since 1940 while sunflower, vegetables, fruits and berries increased by 6.9 times, 1.45 times, and 1.9 times simultaneously. Gross harvest of sugar beet and potatoes has been unchanged for the past 70 yr. Sowing

area under fodder crops decreased from 12 million ha in 1990 to 2.75 million ha in 2008. This decrease caused the number of animals and livestock to decline greatly. In 1990, the number of cows, pigs, sheep and goats, and poultry was 8.4, 19.4, 8.4 and 246 million head, while the corresponding number in 2008 was 2.9, 6.5, 1.7 and 178 million head (Statistics Ukraine 2009).

The west part of the Forest-Steppe Zone with podzolized and leached Chernozems is mainly used for forage crops, winter wheat, sugar beet, flax, and potato production. Typical Chernozems in the Forest-Steppe Zone are used for wheat, sugar beet, barley, rye, soybean, and corn production. The North-Steppe with ordinary Chernozems is the universal zone for the production of most crops, while South Steppe with southern Chernozems is productive for sunflower, soybean, wheat, corn, rice, water melon, tomato, and grape (*Vitis vinifera*). Even without human intervention, Chernozems have the greatest inherent fertility of all Ukrainian soils.

Land Use in Argentina and Uruguay

The Pampean Mollisols are a significant component of the breadbasket of modern times, due to their high agricultural productivity. Consequently these Mollisols have been cropped since the last decade of the 19th century. The main crops are wheat, corn, sorghum (*Sorghum* sp.), barley, soybean and sunflower. The area of soybean has increased steadily in recent years as also happened in Uruguay, while the area of other crops are relatively stable or slightly decreased in the case of sunflower (Fig. 9).

Crop yields in the Pampean region are traditionally higher than those in the Uruguayan Mollisols. This can

Table 1. Crop acreage of Ukraine in 2010 (unit: thousand ha)

Crops	Acreage	Crops	Acreage
Winter and spring wheat	6461	Leguminous plants	409
Winter and spring rye	288	Sorghum	30.7
Rice	29.3	Sunflower	4418
Millet	89.4	Sugar beet	503
Buckwheat	215	Soybean	1070
Haricot	22.0	Winter and spring sape	907
Winter and spring barley	4514	Potato	1408
Maize	2736	Vegetables	460
Oat	329	Feed crops	2509

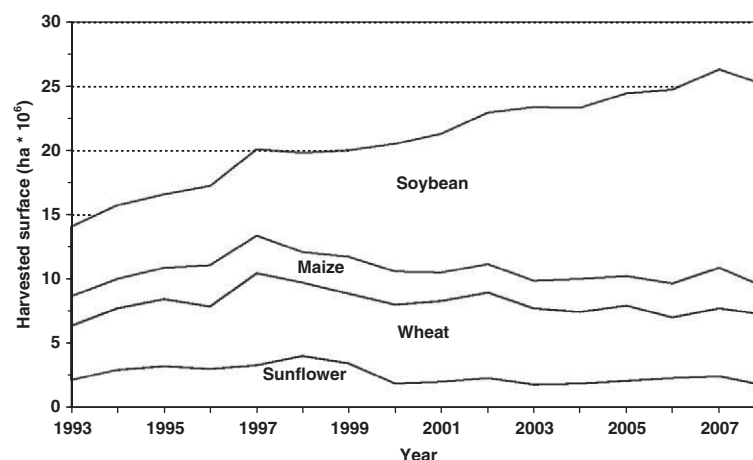


Fig. 9. Harvested area of the main crops in the Pampean Mollisols region, Argentina (MGAP 2010).

be explained by the “agricultural” tradition of the Pampa contrasting to the “livestock farming” tradition of Uruguay though this model in recent years is changing towards a more agricultural system.

Mollisols in Uruguay are used mostly for cattle and sheep grazing due to the productive natural grasslands that can be grazed all year round under a humid and temperate climate without snowfall or dry season. Agriculture was historically confined to the more fertile soils in the southern, southwestern and western regions where the most productive Mollisols developed. Of the total area of 16.5 million ha, 85% was grazing land including 80% natural grassland. This situation prevailed throughout the second half of the 20th century and the beginning of the 21st century. Cropping land (grains, oil seeds and permanent crops) never exceeded 1.3 million ha and the total area under crops decreased to 0.82 million ha in 2000. However, crop land increased rapidly since 2005 with soybeans and wheat being the main contributors to the expansion (Fig. 10).

Although traditional grazing took place on natural grasslands, the improvement of forage production by sod seeding and seeding of pastures and forage crops since the 1960s became progressively more and more important in both cattle farms and dairy farms. As a result, improved pastures including annual forage crops increased 75% between 1990 and 2000 (from 6.5 to 13.2% of total land area). Yet improved pastures are mostly concentrated in the south and southwest of the country, which is also the region with the highest proportion of annual crops, and thus the area is currently under the most intensive land use. Pastures in the southwestern and western regions became progressively associated with crops in rotations since many farmers in Uruguay combined agriculture with cattle raising. This system was highly beneficial for both crops and forage production and soil organic matter conservation.

Land use in Northeast China

There are 14.7×10^4 km² of Mollisols in northeast China that are under cultivation for crop production (Table 2). This accounts for 42.3% of the total continuous calculated area of 34.8×10^4 km². Although the total area of Mollisols in Liaoning Province accounts for only 4% of China's Mollisols, it has 71.5% of its Mollisols under cultivation. Conversely, only 23.6% of the Mollisols in the Hulunbeier League of Inner Mongolia Autonomous Region are used for cropland. Throughout China, different suborders of Mollisols are utilized and managed differently with the differences reflecting different rainfalls, growing seasons and local preferences. Four Mollisol suborders are common to northeast China. Albolls are distributed in Heilongjiang and Jilin province only. They account for 31% of the total cropland in the two provinces. Albolls, when found in lowlands, are best suited for rice growing if headwater is available while those located in hilly regions are prone to soil erosion and should be used for afforestation. The Aquolls have lower soil temperature and higher organic matter contents than their better-drained analogs in the region. The main cropping limitation with Aquolls is water logging. Thus, water logging control through agronomic, forestry and engineering measures is the priority. Alternatively, rice planting is recommended if headwater is available. The Ustolls are distributed in sub-humid and sub-arid regions, and vary in land use and management. In sub-humid region with fertile and reasonable precipitation during the growing season, Ustolls are used for crop production such as maize, soybean or wheat, while most of the Ustolls in sub-arid regions are used for livestock production and breeding. Some of the Ustolls continue to have native vegetation consisting of lush and high-quality grasses. These are ideal grazing lands. Udolls cover the center of the Chinese Mollisol area. They are the most important soils for croplands. They are the literal foundation of green food and commodity grain production in China.

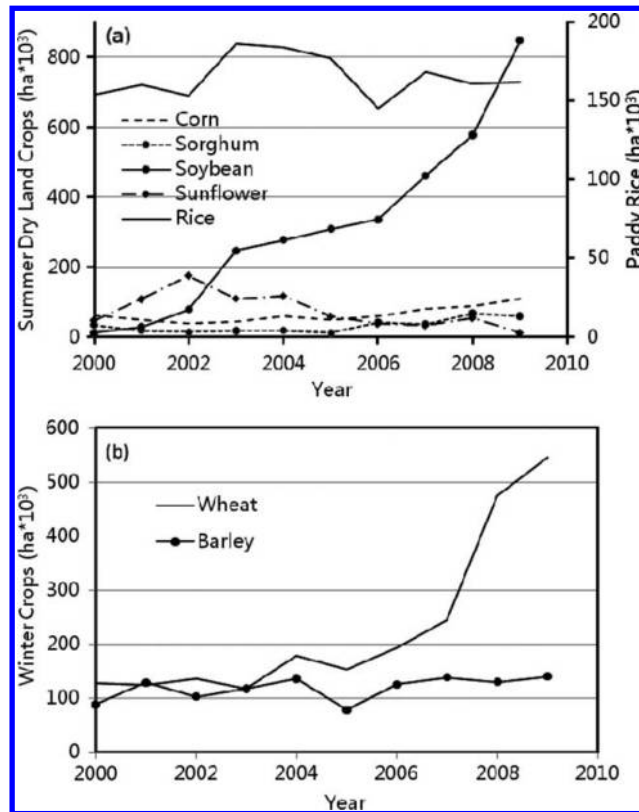


Fig. 10. Cropping area in Uruguay for production of (a) summer crops, (b) winter crops (MGAP, Agriculture and Stockbreeding Statistics Series: www.mgap.gub.uy/estadisticas_agropecuarias).

SOIL MANAGEMENT

Soil Management in the United States of America

In 1975, the USDA noted that Mollisols were some of the most intensively cropped soils in the USA (Soil Survey Staff 1975). That observation is no less true today, with these soils increasingly dedicated to the intensive production of one or two grains on a single farm. Many farms now produce continuous wheat or maize or use some type of grain rotation consisting of two or more of the following: maize, soybean, wheat and sorghum (Padgett et al. 2000). Crops are fertilized commensurate with predicted grain yield. They are tilled according to the preferences of individual farmers. In 2010a typical fertilizer regimen for maize in Iowa is $150 \text{ kg ha}^{-1} \text{ N}$, $30 \text{ kg ha}^{-1} \text{ P}$, and $80 \text{ kg ha}^{-1} \text{ K}$ (nutrient amounts given as elemental forms; please see:

<http://extension.agron.iastate.edu/soilfertility/nrate.aspx> and <http://www.ers.usda.gov/Data/FertilizerUse/> for more detailed fertilizer information). In 1965, typical fertilizer rates were about 50% of those of today. Types of fertilizers used by farmers vary by location and cost although animal manure and anhydrous ammonia are both commonly available over most of the Mollisol region of the United States of America. As yield increased throughout the 20th century, rates of fertilization increased, and the risk of nutrient leaching increased (Barak et al. 1997). Barak and others (1997) recognized long-term nitrogen fertilizers as having a significant acidification effect in the upper soil profile of even high charge soils. Extensive erosion and sedimentation also plague many of the Mollisols that are intensively cropped. For example, some hillslopes having lost more than 1 m from their upland soils and/or gained more than 1 m of sediment in fluvial and colluvial settings (Mokma et al. 1996; Konen 1999; Burras and McLaughlin 2002). Not surprisingly, nutrients are lost during erosion and via leaching into drainage systems. This is creating numerous water-quality and watershed management challenges in the Black Soil regions of the United States of America. Veenstra (2010) in re-characterizing a Typic Hapludoll on a 3% slope in northwest Iowa found its Mollic

Table 2. Cropland percentage of Mollisols

Province	Total area (km^2)	Cropland area (km^2)	%
Sum	347 510	147 027	42.3
Heilongjiang	189 552	89 362	47.1
Jilin	65 831	29 286	44.5
Liaoning	13 834	9 894	71.5
Hulunbeier	78 293	18 485	23.6

epipedon is now 15 cm thinner than it was in 1959. This result is interesting given the site is not thought to have a history of significant erosion. The soil studied also experienced its original granular structure being converted to subangular blocky structure. Extending the results of Veenstra (2010), Barak and others (1997) and other such studies suggests the future use of the USA's Mollisols is somewhat uncertain. Most will certainly remain in highly productive agriculture systems although it is possible that those located in environmentally sensitive areas will be permanently removed from agriculture (Burras et al. 2010).

Soil Management in Canada

The low levels of precipitation and subsequent low productivity of Canadian Mollisols in the semi-arid grassland ecoregions require producers to be particularly concerned with moisture conservation and control of wind erosion. As a result, strip cropping, in which long, narrow fields perpendicular to the prevailing winds are alternately cropped, and summerfallow are common landscape features. Windbreaks consisting of drought tolerant trees such as caragana (*Caragana arborescens*) were also planted as a response to wind erosion during the severe drought years of the 1930s and continue to be used to reduce the effects of wind, but over the past 25 yr reduced tillage and no till cultivation systems have been widely adopted as a soil protection measure (Fig. 11). In the more humid parkland ecoregions soil erosion by water, especially from the peaks in the "knoll and kettle" topography is a concern that has been addressed by more continuous cropping (elimination of summer fallow) and reduced tillage systems (Agriculture and Agri-Food Canada 2003). Similarly, excessive cultivation and summer fallowing have caused a 50% decline in soil organic matter in Canadian prairie soils, resulting in low nitrogen levels and poor surface structure. Recommendations to improve soil organic matter include improved fertilization, continuous cropping, rotations with forage crops and reduced tillage. Salt-affected (saline) soils also affect a considerable area

of cultivated land, and management of these areas focuses on improving water drainage in recharge areas and continuous cropping using salt-tolerant crops and forages. Adequate crop fertilization is a key to soil conservation. The recommended rates of nitrogen fertilizer vary from 30 kg ha^{-1} for spring wheat planted into stubble in the most arid ecoregion to 90 kg ha^{-1} in the most humid ecoregion in Canadian Mollisols. The increasing use of pulse crops and legume forage such as alfalfa and clovers in rotations is also improving the health of these soils.

Soil Management in Ukraine and Russia

Chernozems are prone to soil erosion by water and dehumification, and can lose exchangeable calcium because of human-caused acidification. Because of erosion, the amount of soil organic matter content in weak, medium and severely eroded Chernozems has declined by 15, 25, and 40%, respectively. Other soil properties are worsening after long periods of cultivation with declining crop yields. Because 73.6% of agricultural lands in Forest-Steppe and Steppe zones are under extensive cultivation, the decline in soil organic matter content and other soil properties is ongoing.

The addition of organic matter to the soil, lime application, balanced fertilization, intercropping or mulching, adoption of minimum tillage and irrigation are beneficial practices for Chernozems management. Frequent additions of organic matter, plant residues or manure, to the soil produced more microbial gum and increased ped formation and stability (Medvedev 2002). Plowing of typical chernozem for 54 yr decreased humus content and increased the bulk density. Ten-year application of farm manure and mineral fertilizers increased humus content by 0.3 to 0.6%, especially in minimum tillage plots (Iutynskaya and Patyka 2010). The activities of invertase, urease and protease, were higher with manure and mineral fertilizers compared with manure alone.

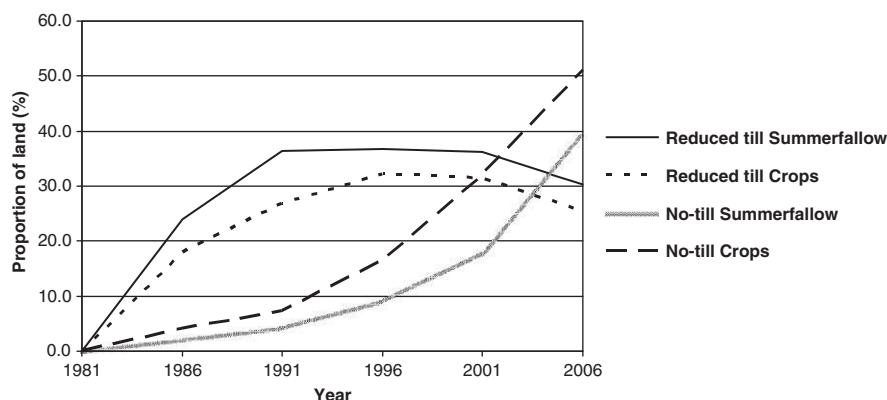


Fig. 11. Changes in the distribution of reduced till and no-till on summer fallow and crops on Canadian Mollisols, 1981–2006.

To prevent soil organic matter loss, the rates of farm manure should be no less than 12–15 t ha⁻¹ yr⁻¹. One ton of straw with 10 kg nitrogen can be a substitute for 5 t of farm manure. Addition of calcium as limestone to the podzolized chernozems contributes to the formation of aggregates and soil structure. The smaller the amount of very coarse aggregates (> 10 mm), the greater the amount of agronomically valuable aggregates (10–0.25 mm) formed in the upper layer of ordinary Chernozem with minimum tillage. Regular practices of lime or gypsum applications are a must to prevent soil decalcination, aggregate destruction, crusting, puddling and other negative consequences of exchangeable calcium shortage.

Long-term cultivation of Black Soils changed their microbiological environment. Autochthonic microorganisms responsible for humus destruction become predominant with conventional tillage (Shikula et al. 1988). In contrast, minimal tillage favors the growth of eutrophic microorganisms; after 18 yr, their populations increased 1.8–2.3 times and nitrifying microorganisms became more abundant.

Fertilizer application had a greater effect on the contents of nitrate and ammonium nitrogen in soil than tillage systems. Twenty years of fertilizer application led to an increase in total phosphorus from 157 mg 100 g⁻¹ (at the beginning) to 195 mg 100 g⁻¹ (manure, maximum rate), 210 mg 100 g⁻¹ (NPK, maximum rate), and 200 mg 100 g⁻¹ (manure + NPK). The Al-P phosphates content increased more than twofold, while Ca-P phosphates changed slightly. The fertilizer rates from N₅₀P₄₅K₄₅ to N₇₅P₆₈K₆₈ increased the yields of all crops, but further increase in rates did not increase yields in the majority of cases.

The use of different soil tillage systems showed that minimum tillage increased enzyme activities by 15 to 30%, while humic acids extracted from typical Chernozem in minimum tillage (10–12 cm) had molecular masses 1.47 times greater than conventional tillage. Minimal tillage had a great influence on the accumulation of NO₃-N and NH₄-N in upper layers, and thus it is the best practice to adopt on these soils (Shikula et al.

1988). In eroded typical Chernozems, minimal tillage and mulch application preserved greater amounts of available water for the plants, with a reduction in runoff and soil loss, and spring barley yield was increased. Steppe Chernozems frequently become dry and need irrigation for economically feasible crop production.

Ukrainian and Russian Chernozems are susceptibility to water and wind erosion, soil organic matter loss, soil compaction and consolidation, deterioration of soil salinity and alkalinity (sodicity) on irrigated lands as well as soil pollution by heavy metals, nuclear wastes, agrochemicals and animal husbandry wastes. To reduce erosional soil loss, Ukrainian land planners propose not to grow intertilled crops on slopes with gradients over 3%, and slopes greater than 5% should not be plowed, but afforested or turned into meadows (grasslands).

Soil Management in Argentina

Pampean Mollisols were originally soils high in organic matter and of very high natural fertility. However, a long period of cropping has resulted in losses of both properties. However, soil organic matter content is still high as a result of the original level in the virgin soils, and even in the western semiarid Pampa, it meets the minimum requirement (1%) of the mollic epipedon. The data in Table 3 provide evidence of the decrease of soil organic matter after a long cropping period that demands establishment of conservation practices to reduce future losses and a deterioration of soil quality.

The high nutrient concentration of Pampean Mollisols allowed a long period of cropping with low fertilization addition to replace extraction by crops, but recent trends of applying fertilizer to these soils have reversed the steady loss of nutrients. Effective reposition of nutrients is increasing, but the ratio of application/extraction is still below 1. The high fertility of Pampean soils explains the late start of systematic fertilization in Argentina.

No-tillage cropping is rapidly increasing in Argentinean Mollisols, which results in reduction of organic matter losses and more sustainable agriculture. No-tillage

Table 3. Change in soil organic matter concentration from virgin to cropped soils in different subregions of the Argentinean Pampa (Duran et al. 2010)

Organic matter content				
Province	Zone	Virgin soils	Cropped soils	Variation (%)
----- (g kg ⁻¹) -----				
Buenos Aires	SW	85.9 (18.5) <i>n</i> = 21	55.3 (9.0) <i>n</i> = 1036	− 35.6
	N	50.5 (10.3) <i>n</i> = 41	29.0 (12.1) <i>n</i> = 2081	− 42.5
Santa Fe	S	42.6 (11.2) <i>n</i> = 6	26.2 (5.1) <i>n</i> = 2853	− 38.4
Cordoba	SE	33.5 (8.4) <i>n</i> = 7	20.2 (5.7) <i>n</i> = 1903	− 39.6
La Pampa	E	34.5 (6.8) <i>n</i> = 7	16.4 (6.1) <i>n</i> = 527	− 52.5

systems are also common in Uruguay and other South American countries.

Soil Management in Uruguay

Duran and Garcia Prechac (2007) recognize four periods defined by the dominant cropping technology and its impacts on soil conservation. (1) 1950–1965: Promotion of mechanical practices (terraces) in rented state-owned farms under very intensive land use. Poor performance and lack of proper management of terraces resulted in abandoning the system; (2) 1965 to present: Introduction and expansion of rotations of crops and pastures; (3) 1975–1990: Inclusion of contour cropping in the crops phase of the rotations; (4) 1990 to present: Introduction of no-tillage systems both in rotations and in continuous cropping systems that have increased rapidly in recent years.

Long-term tillage of arable crops in the older farming areas (southern region) resulted in severe sheet and gully erosion, which affect small holdings with originally fertile and productive Mollisols and Vertisols. These soils are used mainly for orchards and vineyards.

Water erosion is still the main environmental problem for soil management and conservation in Uruguay. Different investigations conclude that erosion is always related to arable cropping, and no clear evidence of influence of overgrazing on soil losses has been identified. Since most of the territory remained under natural grassland until a few years ago (and extensive areas of rangeland still exist) it is not surprising that most of the territory (70%) is not affected by erosion or is only slightly (18%) or moderately eroded (10%); the severely eroded area comprises 2% of the country.

The large increase in the cropping area that took place in past years is a challenge for sustainable land use because of the unquestionable relationship between crop

production and erosion already mentioned. Yet tools and technologies are available to prevent soil losses under cropping systems of increasing intensity rapidly expanding in Uruguay. Some of these tools are: (1) The well-known model (USLE, RUSLE) can be used to anticipate the expected soil losses under a variety of the common cropping systems including both continuous cropping and rotation. The model has been validated for the conditions of soils and rainfall characteristics prevailing in Uruguay (Garcia Prechac 1992; Garcia Prechac et al. 2005). More recently Duran and Garcia Prechac (2007) compiled a complete literature review on this issue. The software based in USLE/RUSLE model is freely available for farmers, extension workers and professional consultants either on CD or from the web site www.fagro.edu.uy (Garcia Prechac et al. 2005). (2) Widespread incorporation of no-tillage systems, which have proved to be the most effective tool in soil conservation. An additional advantage is the sustainability of agriculture in soils previously considered as non-arable because of steep slope or limited depth through the elimination of tillage. (3) Combination of no tillage with crop-pasture rotations is recommended to take advantage of the reduction of soil losses under conventional tillage and the prevention of herbicide-resistant weeds as a result of the alternation of grain crops and pastures. No tillage will also reduce atmospheric CO₂ losses resulting of organic matter oxidation under long-term tillage. The modern crop systems should promote high productivity levels without the negative effects of land use intensification or at least reducing such effects to tolerable levels.

Continuous cropping under conventional tillage resulted in a steady loss of soil organic carbon, while fertilization decreased but did not prevent losses (Fig. 12). On the other hand, crop-pasture rotation

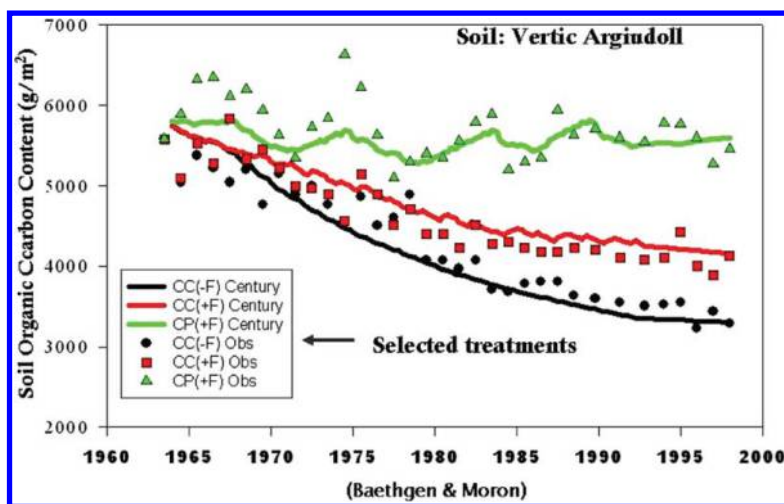


Fig. 12. The observed and predicted soil organic carbon concentration in a long-term rotations experiment in Uruguay by the Century model (started in 1963) (Baethgen and Morón 1994). CC (–F), conventional continuous cropping, not fertilized; CC (+F) id. fertilized; CP (+F), crop-pasture rotation, fertilized.

successfully maintained the initial organic carbon content, since losses during the cropping cycle were reversed in the pasture cycle.

At the beginning of the 1990s, the Government promoted afforestation through a specific national program, which resulted in a substantial increase of forested areas: 180 000 ha at the beginning of the period, 650 000 ha in 2000 and about 800 000 ha at present. The plan provided the technology and finance to support plantations of eucalyptus and pines on soils of good forest suitability, but of relatively low productivity for grains and pasture, with the purpose of developing forestation without affecting the best cropping and grazing areas. Therefore, most forests planted within the framework of the plan are on soils other than Mollisols or Vertisols. These forested lands contribute significantly to a positive balance of the CO₂ cycle, since CO₂ sequestration or fixation is now higher than emissions in the forests, and, together with modern technology in cropping systems, contributes to more sustainable primary production. This does not mean that some uncertainties and challenges may be neglected in order to assure sustainability.

Soil Management in Northeast China

Continuous monoculture, SOC loss and soil erosion are the critical issues in the region. Continuous soybean showed greater declines in soil pH and activity of the main enzymes, as well as lower numbers of bacteria, but more fungi. This imbalance in the microbe populations and deposition of acid compounds in soybean monoculture contribute to the decline in soil fertility (Liu et al. 1990). The following countermeasures have been developed to cope with the negative impact of continuous soybean: adoption of resistant or tolerant cultivars, control of disease and pest insects by seed coating and insecticide application, application of P, K fertilizers and supplemental trace elements, suitable tillage and improved cultivation (Liu and Herbert 2002).

Continuous corn and soybean led not only to a decline in soil biological activity, but also to reduced SOC and N. If continuous corn, soybean, or wheat were to be adopted on the Chinese Mollisols, an average annual rate of decline in soil carbon in the 0- to 90-cm soil profile would be 0.91, 0.97 and 0.48%, respectively (Liu et al. 2005). SOC concentration in soil with the addition of wheat straw in wheat-soybean rotation was 22% greater than that of wheat-soybean alone, and the wheat-sweet clover rotation not only increased the SOC content in all soil depths, but also decreased soil bulk density (Liu et al. 2003). Therefore, the adoption of appropriate crop rotations to increase the quantity and quality of soil organic matter will enhance soil chemical and physical properties and help ensure the long-term sustainability of agriculture in this region of China.

Tillage practices have a major effect on soil properties, the distribution of C and N, and the rate of organic matter decomposition and N mineralization.

Moldboard plowing showed the lowest level of SOC and N content in the profile. Integrated tillage, where tillage system varied with each crop in the rotation (i.e., moldboard plow for wheat, deep chisel for corn and rotatory plow for soybean), had the highest levels of SOC and N in the upper soil layer in the Chinese Mollisols (Liu et al. 2005).

The conversion from conventional tillage to conservation tillage, particularly no till, at an annual rate of 2%, could reverse the loss of SOC in Chinese Mollisols within 20 yr (Yang et al. 2003a). However, this positive effect of conservation tillage on SOC in the Black Soil area of China applies only to severely eroded soil and sloping farmland, but not to flat and low, damp farmland (Qiao et al. 2008).

Annual return of organic materials, either 4225 kg ha⁻¹ of crop residue or 3458 kg ha⁻¹ of manure (which was equal to 90% of the total crop residue returned), could theoretically maintain SOC equilibrium in the Black Soil (Liu et al. 2002). SOC content could be maintained at a relatively stable level with application of sufficient chemical fertilizer, without the return of manure and crop residue, and SOC content was increased with the combination of chemical fertilizer and manure application. This indicates that corn residue and exudates could maintain SOC equilibrium with the current production level and management practices (Yang et al. 2003b, c).

As early as the 1940s, Chinese researchers had recognized the importance of basin tillage in reducing runoff and increasing crop yield. However, basin tillage was only implemented in northeast China in the 1990s. This practice is applicable on all farmlands with a slope steeper than 6%. The general practice is to build a block to form a basin within the furrow at a certain distance along the ridge during the growing season (Yang et al. 1994). Contour tillage is the simplest measure to control soil erosion. It is suitable for use on farmland with a slope less than 10%, and particularly on farmland with slope degree less than 5%. Rat tunnel tillage (forming a rat tunnel at the bottom of the soil layer using machinery) has been adopted since the 1960s, and was initially used in low-lying wet fields. Recently, this form of tillage has been used as a conservational approach in controlling soil loss on gently sloping farmland, and has been adopted widely in state farms.

The use of terraces to prevent soil erosion has only been applied in northeast China in the past two decades. Although various conservation practices could be adopted by land users to control soil erosion and thus increase crop productivity, most are limited by local conditions, and more economic investment is needed. In areas of rural depopulation or increased availability of alternative sources of income to agriculture, the labor needed is often not available. Thus, appropriate government programs and policies are urgently needed to effectively implement these measures. Economic incentives for preventive measures for soil erosion should be

established, i.e., if farmers adopt soil control practices, the government should provide payment. Subsidies for projects such as terrace construction, ridge direction change, seeds for plant strip, and labor resources should go directly to the land users.

SUMMARY

Mollisols are inherently productive and fertile soils. Most of the world's 916 million ha of Mollisols occur in three regions in the northern hemisphere and one region south of the equator, the Parana-La Plata basin of South America. The natural areas from which Mollisols developed are the prairies and steppes that experience temperate and freezing conditions. They are extensively dedicated to cereals and legume production, and are also important soils in pasture, range and forage systems, and thus form the world's natural granary. The majority of the world's Mollisols are affected by water or wind erosion and also by physical or chemical degradation, including SOC loss, aggregate breakdown, crusting, plow pan development, and acidification due to their long agricultural history and improper management. The increasing demand for food security is leading to an intensification of agriculture on Mollisols. Innovations in agricultural practices and policies are still required to guarantee the future sustainability of agriculture in Mollisol regions.

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